SUPPLY CHAIN IMPACTS OF AN INCREASED VEGETABLE DEMAND: THE CASE OF CABBAGE

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ABSTRACT

A number of initiatives have been designed to address food insecurity problems in the U.S., particularly promoting increased consumption of vegetables. However, if the demand for vegetables increases, little is known regarding the impacts of increased demand on the structure of vegetable supply chain. A related relevant question is: if the current supply cannot meet the increase in demand, what are the optimal locations and seasons to expand vegetable production? To address these questions, we develop a transshipment model of the U.S. cabbage sector to assess the impact of closing the gap between current and recommended vegetable intake in the Northeastern region on supply chain structure and costs. We find that the current supply can only meet 40% of increased demand in the Northeastern U.S. In addition, our model suggests that expanding cabbage production to close the intake gap of cabbage consumption leads to de-localization of the supply chain.

BIOGRAPHICAL SKETCH

Dourong Yeh was born in Pittsburgh, Pennsylvania in 1990 and grew up in Taipei, Taiwan. She received her bachelor degree from the Department of Agricultural Economics at National Taiwan University in 2012. Soon after, she started her Master's degree at the Dyson School of Applied Economic and Management at Cornell University. During her graduate study in Cornell University, she focused on the research of food value chain and agricultural marketing.

I would like to dedicate this thesis to my beloved family.

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CHAPTER 1: INTRODUCTION

Food insecurity is generally linked to hunger and poverty problems in developing countries. However, it also affects higher income countries such as the United States (U.S.) and various European countries (Babu et al., 2014). According to the United States Department of Agriculture (USDA), approximately 14.5% of U.S. households are food-insecure. That is, these households were, at times, lack of access to adequate food for an active, healthy life for all household members (USDA ERS, 2012a).

Food security exists when all people, at all times, have physical, social and economic access to sufficient food which meets their dietary needs and food preferences for an active and healthy life (FAO, 1996). The core determinants of food security are food access and food utilization. Food access means the physical and economic access to food, whereas food utilization relates to how food consumed is translated into nutritional and health benefits to individuals. Food security is typically measured by comparing data on actual versus recommended intakes of essential food products, including the levels of nutrients that are necessary for individuals to enjoy good health (Babu et al., 2014).

In the U.S., government programs such as Supplemental Nutrition Assistance Program (formerly known as the Food Stamp Program) are designed to address food access problems. In contrast, food insecurity problems associated with food utilization are often harder to solve. In the U.S., for example, the majority of food-insecure households tend to avoid substantial reductions or disruptions in food intakes by relying on fewer basic foods and by reducing the variety of their diets. This often results in inappropriate intakes of micronutrients (USDA ERS, 2012a). This is an important problem, given that the consumption of micronutrients-rich products such as fruits and vegetables is already typically deficient in U.S. food insecure households.

According to the USDA, the estimated daily intake of fruits and vegetables in the U.S. remains well below recommended levels, especially for dark green vegetables (USDA ERS, 2004). In response, the past decade has seen a number of both public and private interventions designed to emphasize the benefits of increased vegetables consumption. For example, one of the current large joint public/private initiatives in the U.S is the “Fruits & Veggies – More Matters” campaign, which promotes healthy meal planning guidelines among U.S. households.

Given that food insecurity is a problem in the U.S., important research questions include: if the demand for vegetables increases, what are the impacts on the corresponding supply chains? Can the current supply satisfy the increase in demand? Moreover, if there is a demand increase in a particular region, where would the additional supply be likely to come from? We focus on the case of cabbage to examine these research questions. Cabbage is a relevant vegetable product to focus on for several reasons. First, dark green vegetables have been highlighted for their health benefits. In addition, there is a big gap between actual and recommended intake of dark green vegetables in the country. We thereby anticipate that cabbage may experience large demand increase resulting from initiatives aiming at increasing vegetable per capita consumption. Moreover, cabbage is one of the most popular dark green vegetables consumed in all regions of the U.S. It is amenable to storage, and it is produced in a large number of supply locations in different seasons of the calendar year. Therefore, lessons learned from cabbage can be applied to the analysis of other vegetables, particularly for dark greens.

In this study, we develop a transshipment model of the U.S. cabbage supply chain, including production, storage and consumption sectors. We employ this model to assess the impacts of closing the cabbage consumption gap on supply chains structure and costs. We then simulate scenarios of increased consumption focusing on the Northeastern U.S., and we identify the optimal supply responses to satisfy total demand while minimizing overall supply chain costs. We contribute to the literature by estimating the impacts of demand increase on supply chain structure and estimating the optimal supply locations-seasons to expand cabbage production.

This study is organized as follows. After this introduction, we discuss the literature on food supply chains and provide background information of the U.S. cabbage supply chain. Next, we describe the optimization model formulation and the data used to calibrate the model. Subsequently, we explain the scenarios, present our results and discuss the implications of the study. Lastly, we conclude with a discussion of the implications for decision makers, acknowledging the limitations and proposing areas for future research.

CHAPTER 2: LITERATURE REVIEW

Food supply chains have received considerable attention from researchers, given that food products are related to public health and agricultural production is closely linked to environmental impacts (Ahumada & Villalobos, 2009). Studies that analyze food supply chain structure and performance can be categorized into two major categories. One category focuses on evaluating interventions aimed at improving supply chain performance in multiple dimensions (e.g., food safety, localization of food system, etc.). The other category emphasizes how exogenous shocks affect food supply chains' performance and structure (e.g., climate change, globalization of food supply chain, etc.).

First, we consider food supply chain studies that examine optimal strategies or interventions to reach specific supply chain objectives. This stream of studies focus primarily on localization of food supply chains and on environmental impacts. Studies address the impacts of localization associated with activities along the food supply chain, the consumer preferences toward local food, and some compares the environmental indicators such as carbon emission between conventional and shorten food supply chain (Coley et al., 2009; Conner et al., 2009; Ilbery & Maye, 2005; Marletto & Sillig, 2014; Nicholson et al., 2011; Sirieix et al., 2008; Thilmany et al., 2008). Marletto & Sillig (2014), for instance, estimate that the mainstream food chain can cause more pollution than local food supply chain, focusing on transportation for the case of canned tomato in Italy. Coley et al. (2009), for its part, suggests that carbon emissions from local food supply chains (mainly caused by consumer driving to the local farm shop) might be greater than emissions from conventional chain.

Other studies that impact of intervention focus on improving the sustainability performance of food supply chain s in aspects such as increasing product quality, reducing greenhouse gas emissions, assuring food safety, and enhancing consumer confidence (Aung & Chang, 2014; Bourlakis et al., 2014; Egilmez et al., 2014; Fraser & Monteiro, 2009; Garcia Martinez, 2010; Garnett, 2011; Rong et al., 2011). For example, Aung & Chang (2014) indicate the importance of having a good traceability system for the assurance of food safety and for enhancing consumer confidence. Fraser & Monteiro (2009) develop a conceptual framework for choosing the most cost-effective supply chain intervention to improve food safety. In addition, on the topic of sustainability performance, Bourlakis et al. (2014) uses key indicators such as efficiency and product quality to understand the sustainability performance of the dairy supply chain in Greece. Garnett (2011) shows that in order to lower greenhouse gas emissions, it is necessary to design interventions to shift food consumption patterns from diets rich in greenhouse-gas-intensive meat and dairy food to other food products associated with smaller environmental impacts.

The second primary area of food supply chain research focuses on the impacts of exogenous shocks. These can be divided into supply-side and demand-side shocks. Example of the former are studies examining the impacts of climate change on food supply chains. Jacxsens et al. (2010), for example, evaluates how climate change affects the performance of fresh produce logistic chain, particularly for microbiological food safety issue. Fleming et al. (2014) finds that climate change impacts are only well understood at the harvest stage but not at other stages of the Australian seafood supply chain. Other supply-side shocks such as globalization or internationalization are also addressed in past food supply chain studies (Boehlje, 1999; Cheshire & Woods, 2013; Fraser, 2006; Lorentz et al., 2013). Cheshire & Woods (2013), for instance, explore the advantages that can be brought by globalization of food supply chain (e.g., direct trading with international partners, learning international best practice in farm efficiency, etc.) for farmers in Australia.

While a number of studies have focused on the effects of supply-side shocks, we know far less about how demand-side shocks affect the performance of food supply chains. One exception is Pingali (2007), which discusses the transformation of the Asian food supply chain systems in response to Westernization of diets. However, very little is known about the impacts of vegetable consumption changes on the food supply chain structure. Therefore, we contribute to the literature by developing an optimization model of the U.S. cabbage sector to understand the impacts of the demand increase (arising from closing the gap between actual versus recommended intakes of dark green vegetables) on supply chain structure, costs, wholesale prices, and the extent of food system localization (e.g., the average distance traveled by the commodity, the proportion of demand that is satisfied by the regional supply, etc.).

CHAPTER 3: METHODS

In this paper, we develop a supply chain transshipment model, including production, storage and transportation, to identify the optimal structure, estimate the impacts of increased demand on the performance of supply chain, and assess the optimal supply response for the U.S. cabbage sector. This mathematical programming model determines the optimal production, storage, and shipments of cabbage from supply locations to demand locations that minimize the total supply chain costs. While the product flow is constrained by the production capacity and shrinkage resulting from storing cabbage, total shipments from supply and storage locations have to meet consumer demand in each demand location in each season.

Our model is spatially disaggregated and takes into account seasonality in both production and consumption. The external inputs of this model include seasonal supply and demand, regional production and storage costs, and national transportation costs. Given these inputs, the model solves for optimal production level, stored quantities and product flows that minimize the total costs in each season.

The model also provides the resulting seasonal marginal values of each supply location and the seasonal shadow prices of each demand location. The seasonal marginal values of each supply location can be interpreted as the decrease of total supply chain costs that could be brought if an additional acre is allocated to that particular supply location in that season. These marginal values of the supply locations can be viewed as the indicators of the land value at each supply location in each season. In addition, under perfect competition, the seasonal shadow prices of the demand locations can be interpreted as the wholesale prices at each demand location at each season.

Our approach to assess the impacts of closing the gap between actual and recommended cabbage consumption consists two steps. We first examine the maximum demand increase in the Northeastern U.S. that can be satisfied under the existing supply capability. Second, we evaluate the optimal production expansion for meeting the potential demand increase up to the recommended dark green vegetable consumption in the Northeastern U.S. We assume consumption remains the same for rest of the country. This model provides information on the cost-minimizing acreage expansion for the potential demand increase of cabbage in the Northeast, as well as informs the resulting changes of costs, wholesale prices, optimal production and storage quantities, optimal product flow, and the average distance traveled by the commodity.

3.1. Cabbage supply, storage, transportation, and consumption data

The data employed to calibrate the model includes seasonal acreages allocated to cabbage; seasonal production costs and yields at each supply location; storage costs at each supply location; seasonal quantities demanded; transportation costs per mile; and distance between supply locations to demand locations.

Figure 1 illustrates the U.S. cabbage supply chain. In this study, we only consider cabbage for both fresh market and coleslaw, but not processed cabbage used for the production of sauerkraut. Fresh market cabbage is also traded internationally. According to Economics Research Service (USDA, 2010), the U.S. imported 137 million pounds of cabbage from Canada and Mexico in 2010, which accounting for about 12% of annual consumption. In addition, the U.S. exported about 60 million pounds of cabbage mainly to Canada and Mexico in 2010, which accounts for about 3% of total cabbage production in the U.S.

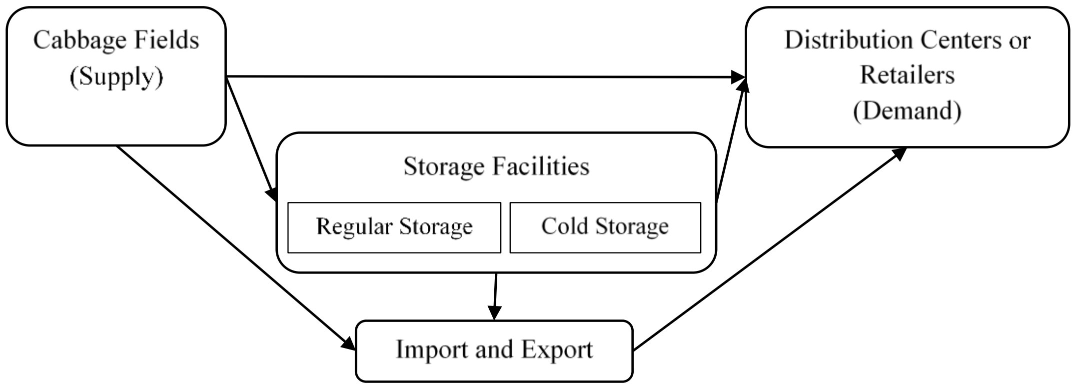


Figure 1. Diagram of the fresh cabbage supply chain

We identified total 27 supply locations in the model, which includes 15 main production states of cabbage in the U.S and accounts the net imports from Mexico and Canada to the U.S. The state level production is disaggregated whenever the data allows doing so. The cabbage growing seasons differ among production regions. For example, California can provide year-round production, while cold climate regions, such as New York, can only produce in the summer and fall seasons. Table 1 presents the estimated seasonal acreage and yields of the U.S. supply locations, and Figure 2 illustrates the sizes and geographical comparison of the domestic supply locations in each season.

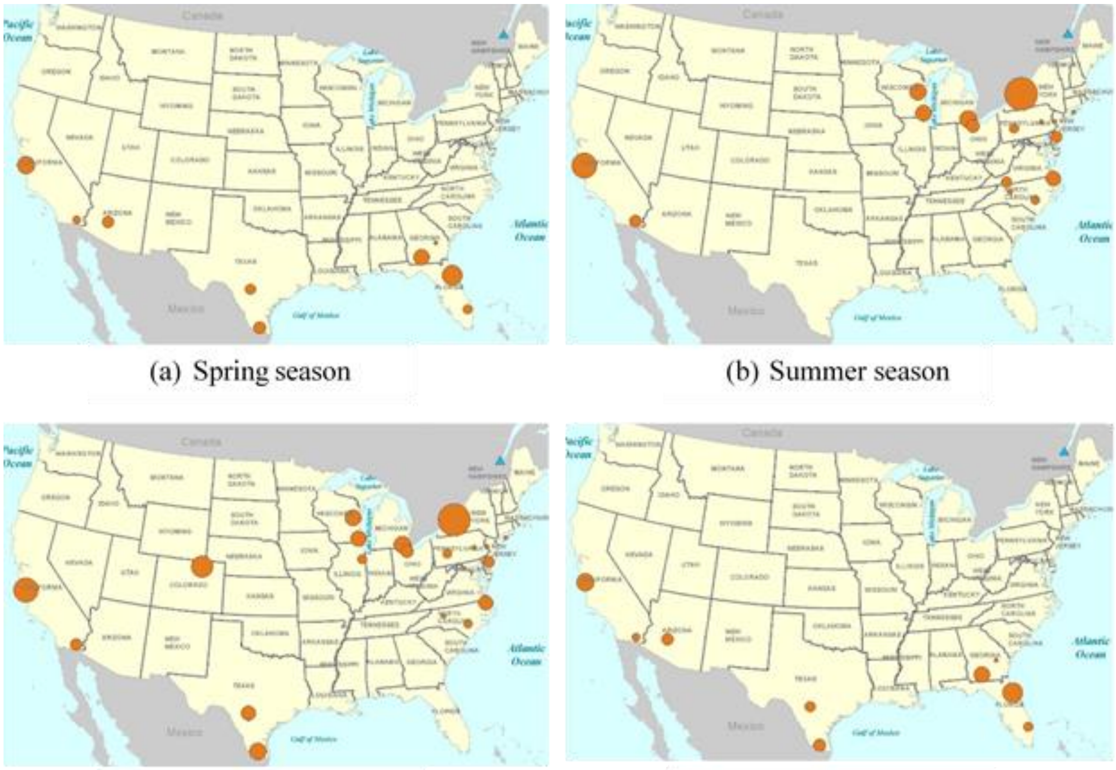
According to USDA (2012), California has the largest annual cabbage production acreage (about 15,800 acres in total), followed by New York (10,900 acres) and Florida (9,900 acres). We regionally adjust the production costs estimates by different input costs (wage, land rent, electricity, gasoline, fertilizer, herbicides, etc.)

from crop budgets estimation published by International Agricultural Trade and Policy Center, University of Florida (2009).

Table 1. Estimated U.S. cabbage acreage and yield at each domestic supply location at each season

Domestic supply locations	Cabbage acreage				Yield
	Spring	Summer	Fall	Winter	(cwt/acre)
Arizona	1450	0	0	1450	418
California, west	3238	3238	3238	3238	390
California, south	712	712	712	712	390
Colorado	0	0	2500	0	443
Florida, northeast	4027	0	0	4027	328
Florida, southeast	923	0	0	923	328
Georgia, south	2630	0	0	2630	279
Georgia, mid-east	171	0	0	171	279
Illinois	0	0	487	0	219
Michigan	0	1480	1480	0	290
New Jersey, south	0	650	650	0	351
New Jersey, north	0	91	91	0	351
New York, northwest	0	5572	5572	0	428
New York, southeast	0	89	89	0	428
North Carolina, east	0	1132	1132	0	224
North Carolina, central	0	380	380	0	224
North Carolina, west	0	143	143	0	224
Ohio	0	862	862	0	318
Pennsylvania, west	0	435	435	0	204
Pennsylvania, east	0	110	110	0	204
Texas, south	1480	0	1480	1480	329
Texas, mid-south	1136	0	1136	1136	329
Virginia	0	600	0	0	253
Wisconsin, mid-east	0	1378	1378	0	224
Wisconsin, south	0	1320	1320	0	224

Source: Author's estimation from Census of Agriculture (USDA-NASS, 2012).



(a) Spring season (b) Summer season

(c) Fall season (d) Winter season

Figure 2. Aggregated U.S. cabbage supply locations and the sizes of land available in each season

The model has total 77 demand locations, including Canada as one demand location in the spring season to account the net exports from U.S. to Canada in that season. We use the large metropolitan statistical areas (MSAs) (US Census, 2010) to define the 32 demand locations in the Northeastern U.S. The Northeastern U.S includes Connecticut, Massachusetts, Maine, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island and Vermont. For the rest of the U.S., we include the top 20 largest MSAs and define one demand location per state at the center of population for states without large MSAs. Appendix 2 includes the lists of domestic demand locations. We calculate cabbage consumption based on USDA's per capita disappearance (USDA ERS, 2012b). Consumption is allocated to each demand location by the population levels (US Census, 2010). The consumption seasonality is estimated using the monthly shipment of U.S fresh market cabbage as a proxy (Table 2).

Table 2. Seasonality of fresh cabbage shipment, as a proxy of demand seasonality

Seasons	Share (%)
Spring	29
Summer	19
Fall	25
Winter	27
Total	100

Source: USDA, Economic Research Service, 2010

Storage costs are obtained from a survey conducted among cabbage growers and program leaders of Cornell Cooperative Extension. There are two types of storage for fresh cabbage: regular storage and cold storage. Regular storage is widely used by growers. In this method, cabbage is stored in shaded area with fresh air and the product can be stored for up to 11-15 weeks. Cold storage is employed primarily in the summer harvest season and can extend the storage time to about 6 months.

Storing cabbage implies product losses resulting from shrink and trim loss. According to industry experts, the shrink loss is about 15% for regular storage and 8% for cold storage, and the trim loss is about 10% for regular storage and 16% for cold storage (Hoepting & Klotzbach, 2012). In the model, we assume a total loss of 25% of the quantity after stored. Also, due to the characteristics of fresh cabbage (bulkiness, weight, etc.), the product is generally stored in facilities located near the production locations. Therefore, in this study, we omit the transportation costs between production locations and storage facilities. The transportation costs account for the distance traveled from production or storage locations to the demand locations.

The transportation costs are calculated using the distance traveled and the average truck rates. We use ArcMap, the packaged software of Geographic Information System, to calculate the minimum distances between production/storage locations and demand locations. We use USDA's quarterly agricultural refrigerated truck rates (USDA AMS, 2013) to compute the shipping costs. We assume 45-lb crate is used in transporting cabbage.

3.2. Vegetable intake data and demand shock

According to the Food Consumption Estimates (USDA ERS, 2004), in 2003-2004, the estimated vegetables intakes for adults in U.S. was 1.79 cups per day, including 0.12 cups of dark green vegetables. A more recent study conducted by Eaton et al. (2013) finds a similar estimates of the total vegetables intakes by adults in the U.S. In contrast, the recommended size of vegetables intakes for adults is 2.5-3 cups per day, including 0.21-0.29 cups of dark green vegetables (USDA, 2013). Among all kinds of vegetables, dark green vegetables exhibit the largest gap between estimated consumption and recommended intakes. The per capita consumption gap is about 0.13 cups, which is 108% of current per capita consumption.

After assessing the maximum demand increase in Northeastern U.S. that can be satisfied under the existing supply, we evaluate the optimal production expansion for closing the gap between actual and recommended intake level in the Northeast, which is 108% increase in consumption.

3.3. Model formulation

The model is structured as a large-scale transshipment problem (equations 1-6 below). The problem's objective is to find the optimal product flow (in million pounds) at each season *t* that minimizes the total supply chain costs (equation 1.1-1.3). The optimization problem is formulated mathematically as follows:

(1) Minimize Total Supply Chain Costs= Total Production Costs + Total Storage Costs + Total Transportation Costs

(1.1) $\text{Total Production Cost} = \sum_t \sum_a \left[\frac{(\sum_b AB_{t,a,b} + \sum_c AC_{t,a,c})}{yield_a} * PduCost_{t,a}\right]$

(1.2) $\text{Total Storage Costs} = \sum_t (\sum_a \sum_b \left(AB_{"T",a,b} * StoreCost_{"T+1",b}\right) +$

$\sum_a \sum_b \left(AB_{"T",a,b} * StoreCost_{"T+2",b}\right) - \sum_b \sum_c \left(BC_{"T+1","T",b,c} * StoreCost_{"T+2",b}\right))$

(1.3) $\text{Total Transportation Costs} = \sum_t \sum_a \sum_c (Tcost * AC_{t,a,c} * MileAC_{a,c}) +$

$\sum_t \sum_{t_{in}} \sum_b \sum_c (Tcost * BC_{t,t_{in},b,c} * MileBC_{b,c})$

Subject to:

(2) $\sum_b AB_{t,a,b} + \sum_c AC_{t,a,c} \leq Land_{t,a} * Yield_a$

(3) $\sum_a AC_{t,a,c} + \sum_b \sum_{t_{in}} BC_{t,t_{in},a,c} \geq DemandQuantities_{t,c}$

(4) $\sum_a AB_{"T",a,b} * (1 - StorageLoss) \geq \sum_t \sum_c BC_{"T+1","T",b,c}$

(5) $BC_{"T","T",b,c} = 0$

(6) $BC_{"T+3","T",b,c} = 0$

(7) All choice variables are non-negative

The indices *t*, *a*, *b*, and *c* indicate seasons, supply locations, storage locations, and demand locations, respectively. Product flow is represented by three variables, $AC_{t,a,c}$, $AB_{t,a,b}$, and $BC_{t,t_{in},b,c}$. Cabbage produced at each season can be either shipped directly from supply location *a* to demand location *c*, represented as $AC_{t,a,c}$; or it can be shipped from supply locations *a* to storage locations *b*, represented as $AB_{t,a,b}$, and then shipped from storage location *b* to the consumption locations *c* in the following two seasons, represented as $BC_{t,t_{in},b,c}$, where t_{in} is a subset of *t* indicating the season in which cabbage enters into storage.

In the set of objective function (equation 1.1-1.3), equation 1.1 represents the total production cost which is calculated using $yield_a$, estimated yields (million pounds/acre), and $PduCost_{t,a}$, the average total production costs ($/acre), at each supply location. Equation 1.2 indicates the total storage cost which is calculated using $StoreCost_{t,b}$, average total storage costs of each storage location at each season. We only consider storing cabbage for up to two seasons given the practices used in the industry. Capital *T* denotes one element in the set *t*, which can be either the spring, summer, fall or winter season. The indices *T+1* and *T+2* denote the following one and two seasons after season *T*, respectively. Total transportation cost is shown in equation 1.3, where *Tcost* is the average unit transportation costs (dollars for one million pounds/mile), $MileAC_{a,c}$ and $MileBC_{b,c}$ are the distances in miles between supply or storage locations and demand locations.

The land constraints (equation 2) ensure that the cabbage shipped out from each supply location does not exceed the production capabilities at that location in each season. Seasonal demand constraints (equation 3), for their part, ensure that the quantities shipped to each demand location met the quantities demanded in that demand location in each season. The storage loss is measured by the reduction in quantity supplied (equation 4), where *StorageLoss* is the percentage loss for both common and cold storage. Equation 5 and 6 ensure that all stored cabbage is stored for at most two seasons, and cabbage cannot be stored and shipped out from storage locations within the same season, which is consider as direct shipment to consumption locations. Equation 7 states that all choice variables have to be non-negative.

3.4. Simulation scenarios: the cap of demand increase in Northeastern U.S. and the optimal supply locations to expand acreage

Using the baseline model, we evaluate the maximum demand increase in Northeastern U.S. which can be satisfied by current supply. As it will be shown below, the ability to close the gap between actual and recommended cabbage intakes meet with current supply is quite limited. Therefore, we simulate the changes in the supply chain required to completely close this gap, which means a 108% increase in current per capita consumption. This allows us to evaluate the optimal acreage expansion by supply location and by season to meet the increased demand while minimizing total supply chain costs.

The baseline model solves for the optimal locations and seasons of cabbage acreage expansion by computing the marginal value of land for each production location at each season. As mentioned, the marginal value of land can be interpreted as the decrease of total supply chain costs that could be brought if an additional acre is added at each location in each season. The optimal acreage expansion simulations are done by selecting the location-season with largest absolute marginal value, then we increase the land available to the limit which the current marginal value changes and resolve the model. We then increase the demand to the new cap and use the new marginal values to select the next optimal location-season for acreage expansion, and so forth. We follow this procedure and until the total acreage expansion can meet the assumed level of demand increase.

3.5. Supply chain impact measures

We examine the impacts of the demand shock described above on several key supply chain indicators. These indicators include total supply chain costs, average wholesale prices, and weighted average source distance (WASD) traveled by the product (Carlsson-Kanyama, 1997; Pirog & Benjamin, 2005). We also examine specific impacts for the Northeastern cabbage sector, including changes in the share of regional production in total consumption in the region. This allows us to examine how a demand shock may affect the extent of localization of food systems.

Average wholesale price of cabbage at each demand location can be used as a proxy for retail price at each demand location, given that retail price generally equals to wholesale price plus a markup from the retail operator. In addition, we calculate the average distance traveled by the product using the equation 8 below, which is the mathematical expression to calculate WASD. The purpose of WASD is to understand the average distance traveled by the product, which is a measure commonly used in food system studies.

$$(8) \qquad \text{WASD} = \frac{\sum_t \sum_a \sum_c AC_{t,a,c} * MileAC_{a,c} + \sum_t \sum_{t_{in}} \sum_b \sum_c BC_{t,t_{in},b,c} * MileBC_{b,c}}{\sum_t \sum_a \sum_c AC_{t,a,c} + \sum_t \sum_{t_{in}} \sum_b \sum_c BC_{t,t_{in},b,c}}$$

Moreover, in order to understand the product flow of Northeastern region in depth, we calculate the quantities and proportion of demand in the Northeast that is satisfied by the regional supply (equation 8 and 9 below). *Northeastern Share* can also be interpreted as the degree of self-reliance and localization in the Northeastern U.S.

(9) Northeastern Quantity = $\sum_t \sum_{a_{NE}} \sum_{c_{NE}} AC_{t,a,c} + \sum_t \sum_{t_{in}} \sum_{b_{NE}} \sum_{c_{NE}} BC_{t,t_{in},b,c}$

(10) Northeastern Share = $\frac{\sum_t \sum_{a_{NE}} \sum_{c_{NE}} AC_{t,a,c} + \sum_t \sum_{t_{in}} \sum_{b_{NE}} \sum_{c_{NE}} BC_{t,t_{in},b,c}}{\sum_t \sum_a \sum_{c_{NE}} AC_{t,a,c} + \sum_t \sum_{t_{in}} \sum_b \sum_{c_{NE}} BC_{t,t_{in},b,c}}$

CHAPTER 4: RESULTS

4.1.Baseline values

The baseline optimization model is solved using the General Algebraic Modeling System (GAMS) with CPLEX solver. Table 3 summarizes the baseline results in terms of total costs, seasonal costs, costs of segments and the supply chain impact measures. The baseline model simulation indicates that total supply chain costs of the cabbage sector in 2012 were about $360.8 million, of which 80% is production costs, 18% is transportation costs and 2% is storage costs, in average. Storage costs occur only in the spring, fall and winter seasons; the latter exhibiting the highest storage costs.

Table 3. Baseline results at each season

	Spring	Summer	Fall	Winter	Annual
Costs (million $)					
Production Costs	69	65	86	68	288
Storage Costs	2	0	1	3	6
Transportation Costs	21	12	13	20	67
Total Costs	92	77	101	91	361
Average Wholesale Prices ($/lb)					
All domestic locations	0.235	0.162	0.169	0.213	0.195
Northeastern locations	0.255	0.156	0.172	0.231	0.204
WASD (miles/million lbs)	499	455	363	509	458
Northeastern Share (%)	63	88	81	65	73
Northeastern Quantity (million lbs)	84	77	93	80	334

Demand for cabbage in the U.S. is seasonal, given that consumption is higher in the winter and spring seasons (Table 2). High demand seasons coincide with the lowest supply in cold climate regions. In these two seasons, the demands from cold regions are met by supply from warmer regions and from cabbage that is put into storage. This results in higher transportation and storage costs in the winter and spring seasons. The baseline average distance traveled by the product is about 458 miles per million pounds. Consistent with higher transportation costs in the winter and spring seasons, the WASD is higher in the winter and spring seasons (509 and 499 miles/million pounds, respectively) than in the summer and fall seasons (455 and 363 miles/million pounds, respectively).

The solutions of our baseline model also suggests that the wholesale prices in Northeast for cabbage ($0.204/lb) are slightly higher than the average domestic wholesale prices ($0.195/lb), especially in the spring and winter seasons. This finding is consistent with estimates from National Fruit and Vegetable Retail Report (USDA, 2014), which indicates that the Northeastern region generally faces a higher retail price comparing to other regions in the country.

Table 4 presents the marginal values of land for each domestic supply location in each season. As mentioned, these marginal values can be viewed as the land value for an additional acre in each supply location in each season. A marginal value equals to zero means that the location-season is below its full production capacity, thereby the total supply chain costs will not be affected if we increase the land acreage in that particular supply location-season.

Table 4. Baseline marginal value of land for each domestic supply location in each season[a]

Domestic supply locations	Baseline marginal value ($/acre)			
	Spring	Summer	Fall	Winter
Arizona	2478	-	-	1585
California, west	742	0	0	0
California, south	1213	811	631	434
Colorado	-	-	1352	-
Florida, northeast	2517	-	-	1787
Florida, southeast	2471	-	-	1742
Georgia, south	1523	-	-	927
Georgia, mid-east	1659	-	-	1038
Illinois	-	-	202	-
Michigan	-	967	1341	-
New Jersey, south	-	1132	1695	-
New Jersey, north	-	1141	1739	-
New York, northwest	-	1681	2454	-
New York, southeast	-	2311	3039	-
North Carolina, east	-	0	0	-
North Carolina, central	-	0	94	-
North Carolina, west	-	0	221	-
Ohio	-	722	1139	-
Pennsylvania, west	-	0	0	-
Pennsylvania, east	-	0	0	-
Texas, south	2267	-	887	1523
Texas, mid-south	2494	-	1024	1791
Virginia	-	194	-	-
Wisconsin, mid-east	-	0	0	-
Wisconsin, south	-	0	115	-

[a] The blank location-season indicates that the production location is unable to produce cabbage during that particular season

Southeast New York in the fall season has the highest land value ($3039/acre), followed by mid-south Texas in the spring season ($2494/acre), Arizona in the spring season ($2478/acre), and Northwest New York in the fall season ($2454/acre). These results are consistent with the estimated yields at each supply location (Table 1). The supply locations-seasons with higher land value generally have higher yields than the average of the U.S.

4.2. Simulation results: the cap of demand increase in Northeastern U.S.

Under the current production capacity, we estimate that the domestic cabbage industry can satisfy up to a 40% increase in the demand for cabbage in the Northeastern region. Note that we do not consider the case of expanding imports in this study. In order to further understand the changes of Northeastern supply chain system when facing alternative levels of demand increase (up to the 40% limit) in Northeast, Table 5 presents the supply chain impacts resulting from 15%, 30% and 40% demand increase in the Northeast.

The scenario that the Northeastern consumption increase by 40% is equivalent to which all domestic supply is under full production. The average wholesale prices increase 45% to the baseline value, which is about an extra $0.87 per pound. The increase in wholesale prices is mainly driven by the increase in storage costs, which is 50% higher than the baseline value.

In addition, comparing the scenario of 40% demand increase in Northeast with baseline values, Northeastern U.S. becomes less self-reliant. Although the total production in Northeast increases from 372 million pounds to 445 million pounds, the proportion of demand in Northeast that is satisfied by regional supply becomes lower (from 73% to 69%).

Table 5. Supply chain impacts of increased northeastern consumption

	The Baseline *Value*	Northeastern consumption					
		15% increase		30% increase		40% increase (cap)	
		Value	*% to baseline*[a]	*Value*	*% to baseline*	*Value*	*% to baseline*
Costs (million $)							
Production	288	300	4	314	9	322	12
Storage	6	6	0	8	33	9	50
Transportation	67	69	3	71	6	74	10
Total Costs	361	376	4	392	9	404	12
Average Wholesale Prices ($/lb)							
All domestic locations	0.195	0.202	4	0.228	17	0.282	45
Northeastern locations	0.204	0.212	4	0.242	19	0.299	47
WASD (miles/million lbs)	458	460	0	457	0	468	2
Northeastern Share (%)	73	71	-3	72	-1	69	-5
Northeastern Quantity (million lbs)	334	372	11	431	29	445	33

[a] The percentage changes with respect to the baseline value

4.3. Simulation results: optimal supply locations to expand acreage

Current production can only satisfy a 40% increase in cabbage demand in Northeast region. However, this is insufficient to completely close the 108% gap between current and recommended intakes as discussed above. Therefore, we employ our optimization model to determine the optimal regions and seasons that can enter into production so as to completely close the gap between current and recommended cabbage intakes. Optimality here refers to allocating new acreage to cabbage production based on the marginal value of land at each production location in each season (section 3.4).

Table 6 presents the optimal acreage allocations until satisfying the addition 108% demand increase in the Northeast. The results show that the optimal supply location-season for acreage expansion is the Southeast region of New York State in the fall season, which originally has only 2% of the production capability comparing to Northwest New York (Table 1). It will need an extra of 8,500 acres of land to meet the additional 108% demand increase in the Northeast. However, since Southeast New York currently only has 196 acres in production, it is unrealistic to allocate additional 8,500 acres for cabbage production. Therefore, we again employ the optimal acreage expansion analysis but imposing a maximum of 500 acres that can be used for cabbage production in the Southeastern region of New York State.

Using this addition restriction, our model yields more realistic results. That is, our optimization model suggests that it is efficient to have cabbage acreage expansion in four regions-seasons, namely Southeast New York in the summer and fall seasons, Arizona in the spring season, Northeast Florida in the spring season and Northwest New York in the fall season (Table 6). These additional three optimal supply locations-seasons originally have larger numbers of land available and are the leading production regions (Table 1), so we do not consider putting acreage restriction in this case. The new acreage allocated to the optimal supply locations-seasons are about 38%, 74% and 54% to the current land in production for Arizona in the spring season, Northeast Florida in the spring season and Northwest New York, respectively.

Table 6. Optimal acreage expansion for northeastern consumption to 108% in location-season[a]

Optimal Acreage expansion (acre)	Without acreage limit	With acreage limit
Arizona		
In spring season	-	550
Florida, northeast		
In spring season	-	2973
New York, northwest		
In fall season	-	2998
New York, southeast		
In summer season	-	412[b]
In fall season	8500	412[b]

[a] Only the location-season that is affected by the optimal acreage increase is listed in the table

[b] We limit the total acreage in southeast New York to 500 acres at the summer and fall seasons

Table 7 summarizes the supply chain impacts resulting from employing acreage expansion scenarios to satisfy the 108% demand increase in the Northeast. Comparing changes resulting from the two scenarios with and without land restriction, since the acreage expansion scenario with land restriction on Southeast New York is no longer the most cost-minimizing solution, the total supply chain costs increase from 446 million dollars to 451 million dollars. In addition, the solutions of land restricted scenario has the optimal supply locations further away from Northeastern U.S. Therefore, WASD increases (from 420 miles/million lbs to 480 miles/million lbs), and Northeastern U.S. becomes less self-reliant (Northeastern Share decreases from 79% to 65%).

Subsequently, given that the supply locations are all under full production in the acreage expansion scenario, we compare the results of acreage expansion scenario (with land restriction) to the scenario of 40% demand increase in Northeast U.S under current supply. Result shows that the total storage cost can be 11% lower, while the wholesale prices would be around 10% less if we employ the optimal land allocations ($0.282/lb to $0.252/lb). The proportion of Northeastern demand that is satisfied by regional supply becomes lower (69% to 65%), which is consistent with the increase of WASD (468 miles/million lbs to 480 miles/million lbs).

Table 7. Optimal acreage expansion for increased northeastern consumption

	The Baseline	Northeastern consumption 40% increase (current supply limit)	Optimal acreage expansion for 108% demand increase					
			Without acreage restriction [a]			With acreage restriction on Southeast New York [a]		
	Value	*Value*	*Value*	*% to baseline*	*% to the cap* [c]	*Value*	*% to baseline*	*% to the cap*
Costs (million $)								
Production	288	322	360	25	12	358	24	11
Storage	6	9	12	100	11	8	33	-11
Transportation	67	74	74	10	0	85	27	15
Total Costs	361	404	446	24	10	451	25	12
Average Wholesale Prices ($/lb)								
All domestic locations	0.195	0.282	0.248	27	-12	0.252	29	-11
Northeastern locations	0.204	0.299	0.265	30	-11	0.270	32	-10
WASD (miles/million lbs)	458	468	420	-8	-10	480	5	3
Northeastern Share (%)	73	69	79	8	15	65	-11	-6
Northeastern Quantity (million lbs)	334	445	756	126	70	616	85	38

[a] See Table 6 for details of the optimal land allocations for acreage expansion scenarios

[b] The percentage changes with respect to the baseline value

[c] The percentage changes with respect to the cap of demand increase, which is 40% increase in Northeastern consumption

CHAPTER 5: DISCUSSION

Our model suggests that the existing production capability in U.S. can only meet a 40% increase in the cabbage demand in the Northeastern region of the U.S. Table 5 indicates that, if the production level remains the same and demand increases to the cap, the wholesale prices are expected to increase for about 45%. Though demand for vegetables is relatively price inelastic, a large increase in prices will clearly affect the affordability of this commodity. If demand in the Northeastern U.S. increases, Table 5 suggests that the increase of wholesale prices is mostly caused by changes in storage costs. In other words, under this scenario, more cabbage is stored after harvest in order to meet demand in subsequent seasons. Given that the shrinkage and trimmed loss for storing cabbage is considered as a fixed percentage of weight loss in the model, if there exhibits a 45% increase in wholesale prices, the growers would experience a higher profit loss when storing cabbage.

As a result, facing a potential vegetable demand increase, it is important to understand the optimal locations-seasons for acreage expansion. The model results show that the Southeast region of New York State in the fall season may be the best location-season to expand production for meeting the additional cabbage demand while minimizing supply chain costs. While a large proportion of cabbage production takes place in the west coast and central U.S., this result suggests that the New York State has the relatively high comparative advantage for expanding cabbage production. This result is also consistent with the estimated yields (Table 1) given that New York State has the second highest yield (428 cwt/acre) following Colorado State (443 cwt/acre).

However, it is unlikely that southeastern region of New York State can accommodate such a large increase in production to meet the increased demand. Consequently, we conduct the simulations imposing a limit on the land available for cabbage production in the Southeast New York (500 acres). The new optimal locations to expand cabbage production then include four regions-seasons, namely Southeast New York in the summer and fall seasons, Arizona in the spring season, Northeast Florida in the spring season and northwest New York in the fall season (Table 6). Table 7 summarizes the resulting impacts on the cabbage supply chain performance.

One of the interesting findings is that, comparing the optimal acreage expansion (with acreage limit) to the 40% increased consumption scenario, the Northeastern U.S. becomes less self-reliant. The proportion of demand in Northeast that is satisfied by the regional supply decreases from 69% to 65%. In other words, our findings show that if the cabbage supply chain faces a regional demand shock, such as a dramatic demand increase in the Northeast, the costs-minimizing solution of the model indicates a more nationally-integrated cabbage sector. This is, the supply should move away from localization towards integration at the national level. This result is consistent with the increase in WASD (3% increase), which shows that under the cost-minimizing objective function of the model, the optimal supply locations-seasons for land allocations lead to a higher average distance traveled by the product.

In recent years, increased localization of food supply chains has gotten strong support due to the perceived benefits it might be able to provide in terms of stronger local communities, improved environmental stewardship, and higher consumers' preferences (Holloway et al., 2007; Ilbery & Maye, 2005; Winter, 2003). Though we do not consider those social benefits that might be brought from a localized supply chain system, we argue that under a perfectly competitive market, having the cost-minimizing solution is a suitable indication for understanding the possible demand-side impacts. As wholesale prices can be viewed as the proxy for the retail prices that consumers face, the costs-minimizing solution also points out the supply allocations that would have the smallest negative impacts on consumers in terms of increased prices.

In Table 7, comparing the optimal acreage expansion with 40% demand increase in Northeast under current supply, the wholesale prices can be about 11% lower if we allocate land to the optimal supply locations-seasons. It is important to compare these two scenarios given that the domestic supply is under full production for both scenarios. This result provides information for both public and private sectors to understand the possible impacts resulting from the optimal land allocation to cabbage production.

CHAPTER 6: CONCLUSION

We employed a spatially disaggregated transshipment model of the U.S cabbage sector to analyze the impacts of a regional demand-side shock (i.e., increasing per capita consumption in a particular region of U.S. to close the gap between current and recommended intakes of dark green vegetables) on the structure and performance of the supply chain. This is a relevant question because there are a number of programs and initiatives aiming at solving the food security problems in the U.S. We focus on a cabbage demand shock in the Northeastern U.S. to understand how a demand increase in a particular region influences the national supply chain for this product, including costs, wholesale prices, and the extent of localization of food systems (e.g., the average distance traveled by the product, etc.).

Our simulation results suggest the cabbage wholesale prices may increase by 45% if demand increases in the Northeastern U.S. without increasing land allocated in cabbage production, which would permit about 40% increase in Northeastern consumption. Our model indicates that current cabbage supply can no longer satisfy domestic demand after a 40% per capita consumption increase in Northeast. This estimated cap on demand increase due to fixed production suggests that cabbage acreage must necessarily increase in order to completely close the gap between current and recommended dark green vegetable intakes. Therefore, the analysis of optimal supply locations for acreage expansion provides both policy makers and industry with relevant information to plan for the future.

The optimal acreage expansion scenario shows that the Southeastern region of New York State in the fall season is the best location to expand production. But if we consider land limitation in the area and competition for land with other high-value agricultural products, Arizona in the spring season, Northeast Florida in the spring season and Northwest New York in the fall season are the other three optimal supply locations for acreage expansion. This finding provides useful information for private and public decision makers to allocate land for vegetable production.

We also find that increased demand for cabbage in the Northeastern U.S. may lead to increased national integration of supply chain. In other words, a significant demand shock in the Northeast would in fact de-localize food supply chain. This result contradicts other studies arguing that increased fruit and vegetable consumption can be achieved through increased localization of food supply chains. Given that consumer prices can be calculated after adding the markup of retail operators to the wholesale prices at each demand location, we argue that the cost-minimizing solutions from our model could provide an accurate estimate of the demand-side impacts on the supply chain performance.

While our analysis provides valuable insights on the impacts of demand-side shocks on vegetable supply chain, our model can be used to employ other relevant issues in the vegetable supply chain. For example, if a certain supply region would like to expand production and develop a more localized supply chain system, our model can be adapted to assess the impacts of localization in various performance dimensions, such as the changes in average distances traveled by the product, which are important to understand environmental benefits of increased food system localization.

Lastly, there are limitations that should be addressed in future research. First, our study assumes perfectly competitive markets and cost minimizing behavior of firms participating in the cabbage supply chain. This assumption should be validated by developing statistical tests based on time-series analysis to test for market integration and imperfect competition. Second, although we do employ acreage expansion scenario with acreage limit in Southeastern New York, the opportunity costs of shifting land into cabbage production from other high-value crops should be taken into account. Comparing the two supply locations in New York State, the only difference in our model is the location. Southeast New York is closer to New York City, one of the largest metropolitan areas with large cabbage consumption. As a result, in our model, this supply location has advantages due to lower transportation costs in comparison to Northwest New York. However, land costs are expected to be much higher in Southeast New York and growers might prefer to produce other high-value crops rather than cabbage. Third, our model omits the case of processed cabbage. While, in reality, the markets for fresh and processed cabbage are interconnected and both affect grower production decisions. Although the processed cabbage has only a small share of the market, the analysis can be extended to incorporate processed cabbage.

APPENDIX

Appendix 1. Lists of domestic supply locations

	Center county for the region
Arizona	Maricopa, AZ
California, west	Monterey, CA
California, south	Imperial, CA
Colorado	Weld, CO
Florida, northeast	Flagler, FL
Florida, southeast	Palm Beach, FL
Georgia, south	Colquitt, GA
Georgia, mid-east	Toombs, GA
Illinois	Kankakee, IL
Michigan	Monroe, MI
New Jersey, south	Cumberland, NJ
New Jersey, north	Hunterdon, NJ
New York, northwest	Monroe, NY
New York, southeast	Suffolk, NY
North Carolina, east	Pasquotank, NC
North Carolina, central	Sampson, NC
North Carolina, west	Davie, NC
Ohio	Sandusky, OH
Pennsylvania, west	Indiana, PA
Pennsylvania, east	Schuylkill, PA
Texas, south	Hidalgo, TX
Texas, mid-south	Medina, TX
Virginia	Carroll, VA
Wisconsin, mid-east	Outagamie, WI
Wisconsin, south	Racine, WI

Appendix 2. Lists of domestic demand locations

1	Alabama
2	Albany-Schenectady-Troy, NY
3	Allentown-Bethlehem-Easton, PA-NJ
4	Arkansas
5	Atlanta-Sandy Springs-Marietta, GA
6	Atlantic City-Hammonton, NJ
7	Baltimore-Towson, MD
8	Binghamton, NY
9	Boston-Cambridge-Quincy, MA-NH
10	Bridgeport-Stamford-Norwalk, CT
11	Buffalo-Niagara Falls, NY
12	Chicago-Joliet-Naperville, IL-IN-WI
13	Dallas-Fort Worth-Arlington, TX
14	Delaware
15	Denver-Aurora-Broomfield, CO \1
16	Detroit-Warren-Livonia, MI
17	Erie, PA
18	Harrisburg-Carlisle, PA
19	Hartford-West Hartford-East Hartford, CT
20	Houston-Sugar Land-Baytown, TX
21	Idaho
22	Indiana
23	Iowa
24	Kansas
25	Kentucky
26	Lancaster, PA
27	Los Angeles-Long Beach-Santa Ana, CA
28	Louisiana
29	Manchester-Nashua, NH
30	Miami-Fort Lauderdale-Pompano Beach, FL
31	Minneapolis-St. Paul-Bloomington, MN-WI
32	Mississippi
33	Montana
34	Nebraska
35	Nevada
36	New Haven-Milford, CT
37	New Mexico
38	New York-Northern New Jersey-Long Island, NY-NJ-PA
39	North Carolina
40	North Dakota
41	Norwich-New London, CT
42	Ohio
43	Oklahoma
44	Oregon

45	Philadelphia-Camden-Wilmington, PA-NJ-DE-MD
46	Phoenix-Mesa-Glendale, AZ
47	Pittsburgh, PA
48	Portland-South Portland-Biddeford, ME
49	Poughkeepsie-Newburgh-Middletown, NY
50	Providence-New Bedford-Fall River, RI-MA
51	Reading, PA
52	Riverside-San Bernardino-Ontario, CA
53	Rochester, NY
54	San Diego-Carlsbad-San Marcos, CA
55	San Francisco-Oakland-Fremont, CA
56	Scranton--Wilkes-Barre, PA
57	Seattle-Tacoma-Bellevue, WA
58	South Carolina
59	South Dakota
60	Springfield, MA
61	St. Louis, MO-IL
62	Syracuse, NY
63	Tampa-St. Petersburg-Clearwater, FL
64	Tennessee
65	Trenton-Ewing, NJ
66	Utah
67	Utica-Rome, NY
68	Vermont
69	Virginia
70	Washington-Arlington-Alexandria, DC-VA-MD-WV
71	West Virginia
72	Wisconsin
73	Worcester, MA
74	Wyoming
75	York-Hanover, PA
76	Youngstown-Warren-Boardman, OH-PA

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